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Thermo acoustic - MHD electrical Generator

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Abstract

The thermo-acoustic generators offer a unique means of converting thermal energy into mechanical energy without any moving parts and without fluid circulation. They are comparable to the Stirling engine with the advantage of much greater simplicity. They are therefore natural candidates for special uses where interventions are limited. The problem to solve is transforming the mechanical energy into electrical energy. MHD generators offer excellent opportunities in this area, particularly by using the mechanisms of induction. The work concerns the combination of a thermo-acoustic generator with an induction generator of a new concept for obtaining electric current with adjustable voltage and current strength, delivered at the thermo-acoustic wave frequency. The system has been subjected to numerical simulation. However, an experimental program is being studied in collaboration with industrial and academic partners. The exploitation of the process by using a solar collector (parabolic or cylindrically-parabolic) is envisaged with the aim to produce electricity, for example, in isolate villages

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1. Introduction

The thermo-acoustic generator allows the production of mechanical energy. This energy is associated with the generation of a pressure wave producing oscillations of velocity in a compressible fluid. The conversion of mechanical energy into electricity can be achieved in different ways. It is possible, for example, to use piezo-electricity. However, this simple method gives only a small level of power (few watts maximum). Other solutions could be based on the use of a rotating machine. This possibility is necessarily accompanied by moving parts which limits the interest in it, because the aim is the construction of a generator without moving parts. Other possibilities are based on the use of linear induction machines using solid pistons to create variations of magnetic flux in a coil and thus generate

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electrical power. Although much simpler than the previous proposals, this option also brings strong mechanical parts in motion.

The possibility of connecting the thermo-acoustic effect with the MHD effect is very attractive; it does not involve any moving parts. It is interesting to note that this type of generator, based on the use of liquid metal, has already been proposed and successfully tested. The principle is based on the concept of electromagnetic pumps working in generators. The pumps transform electromagnetic energy into mechanical energy; exactly the reverse transfer occurs in generators. In this concept, two types of machines can be considered: conduction machines", Marty [1991], which produce strong electric currents at low voltage and require electrodes to collect the produced current, what may be a handicap for questions of water tightness, and induction machines "Joussellin and all [1989] ", which produce electric current with adjustable strength and voltage and do not require any electrodes.

Both possibilities can be envisaged for coupling the MHD generator with a thermo-acoustic generator. A study of conduction generators coupled with thermo-acoustic effect has been carried out in the framework of a thesis "Vogin [2005] " and published "Vogin and all [2007] ". This system theoretically allows excellent efficiency, but with load conditions that are not very realistic.

The possibility of using the induction mechanism seems more attractive and more realistic considering the fact that thermo-acoustic generators deliver mechanical energy directly in the alternating form, perfectly compatible with the use of MHD generators based on variations of magnetic flux. The proposed system involves a new type of induction generator using the oscillations of liquid metal produced by the thermo-acoustic effect.

2. Description of the generator

The principle of the induction MHD generator "Ramee and all [2009] " is shown in Figure 1. The system is based on the oscillation of a liquid metal in the presence of an imposed permanent magnetic field. The interaction of the metal velocity oscillations with the magnetic field induces an electric current pulsating at the same frequency as the velocity oscillations. These pulsations, in turn, create an induced magnetic field and a pulsating magnetic flux which induces an electric current in the coil connected with the load. The characteristics of the produced electric current depend on the characteristic of the coil and the load.

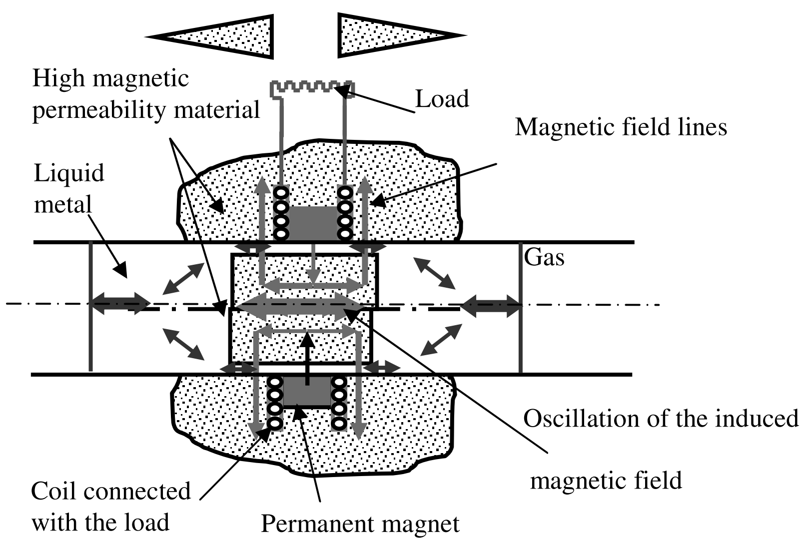

Fig. 1. Principle of the MHD induction generator

The shape of the channel in which the fluid oscillates can be modified to obtain better energy efficiency.

3. Global system description

The MHD generator itself must be coupled with the thermo-acoustic generator to obtain an autonomous system. The proposal is shown in Figure 2.

The MHD generator can be placed between two thermo-acoustic tubes. The return circuit corresponding to the use of traveling wave can be removed. In that case, the MHD generator would be sandwiched between two standing wave tubes. The pressure fluctuations generated on both sides of the MHD generator produce oscillations of liquid metal which, by the interaction with the applied magnetic field, imposed by a permanent magnet, produce electric current.

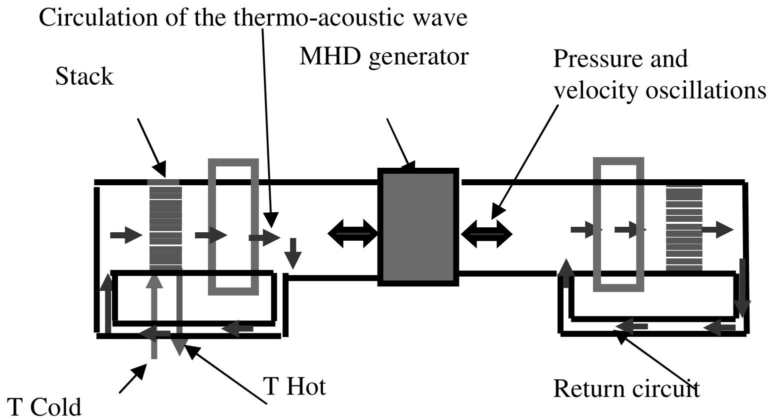

Fig. 2. The concept of the electrical generator, combination of thermo-acoustic and MHD generators.

The proposed system is based on the use of gas as thermodynamic fluid providing mechanical energy and of liquid metal (sodium) in the MHD generator to convert mechanical energy into electrical energy. Sodium is the most appropriate fluid for this energy transfer, because of its low density, limiting the effects due to inertia, and also because of its high electrical conductivity which makes it sensitive to the influence of a magnetic field.

The problem of the liquid-gas interface can be solved easily in an application on the earth by using gravity, because, in this case, the MHD generator can be put at the bottom of the system and the two thermo-acoustic parts at the top.

4. The models used.

4.1. For the thermo-acoustic part.

A detailed description is rather long and exceeds in size the text of this paper.
For the thermo-acoustic generator, the classical model proposed by "Swift and all[1985] " is used, which

consists of a linearization of the Navier-Stokes, continuity, entropy and energy equations completed by a state equation to describe the evolution of the main characteristic of the fluid depending on temperature and pressure. By combination, it is possible to reduce the description of the generator to a system of three independent equations, which, for the stack and thermobuffer, have the form:

$$\frac{dU}{dx} = -Ap + B\frac{dT_m}{dx}U \tag{1}$$

$$\dot{H}_2 = C\,\mathrm{Re}[p\tilde{U}] + \left(D|U|^2 - K A_{gas} - K_s A_{solid}\right)\frac{dT_m}{dx} \tag{2}$$

$$\frac{dp}{dx} = -EU \tag{3}$$

These equations model the evolution of the complex amplitudes p and U of the pressure and volume flow waves and the mean temperature Tm along the longitudinal direction x of the generator element, and $\dot{H}_2$ is the enthalpy flow in the element. K and Ks are the heat conductivities of the fluid and the stack material. A_{gas} and A_{solid} are gas and solid material cross section areas. The complex coefficients A, B, E and real coefficients C, D are determined by the geometry of the machine, the type of the generator element, and the main properties of the fluid and stack material.

The equations for ordinary ducts are similar except that the mean temperature is assumed to be constant in ducts and the equation coefficients are calculated differently, see "Swift [2010] ".The solution of this system allows predicting the evolution of velocity, pressure and mean temperature along the stack when the introduced thermal power Q is fixed.

The calculation results of the thermo-acoustic engine equations are the pressure and volume flow wave amplitudes pout and U_{out} at the joint with the MHD engine. The calculated pout and U_{out} values depend on the target value of introduced heat Q, the stack cold end temperature Tc, the pressure amplitude pentry at the stack entry, which is used as the initial condition for the pressure equation integration, and the angular frequency of fluctuations ω.

4.2. For the MHD part.

The MHD generator has been modeled under the assumption of low magnetic Reynolds number, which allows neglecting the induced field compared to the applied one, and neglecting the effects of viscosity and turbulence. The velocity field in the cross section of the generator is considered constant. The basic equation system used is deduced from the Maxwell equations and the Ohm's law and by integration of the Navier Stokes equation along a stream line in the MHD generator.

$$\frac{db}{dx} + \frac{e'}{e}b - \frac{i\omega\mu_0\sigma}{r}\int_0^x b r dx' = -\mu_0\sigma v B \tag{4}$$

$$-b_s e_s = \mu_0 N I_R \tag{5}$$

$$-i\omega\Phi_t = R I_R - \frac{iI_R}{C\omega} \tag{6}$$

$$-2\, p_{in} = -\rho \int_A^B i\, \omega\, v\, ds + \rho \int_A^B f_{EM}\, ds \tag{7}$$

In these equations, b represents the amplitude of the induced magnetic field component that is perpendicular to the longitudinal direction x along a narrow gap (bs is its value at the gap exit), B is the perpendicular component of the imposed permanent magnetic field, r is the distance of a gap element to the symmetry axis (radius), and e is the gap thickness (es is the gap thickness at the gap exit). □t is the total magnetic flux crossing the N wires of the coil connected to the load; □ is electric conductivity of the liquid metal in the generator, and v is the amplitude of the velocity fluctuations. R, IR, and C are respectively the load resistance, the induced current on the load, and the capacitance used to improve the efficiency of the generator by compensation of the self.

The last equation [7] concerns the integration of a simplified Navier-Stokes equation along a streamline in the generator from its end A to the end B; pin is the amplitude of the pressure fluctuation at the end A of the MHD generator, velocity amplitude v at different locations is calculated from a constant melt volume flow rate Uin through the engine, and fEM is the amplitude of the electromagnetic force density in the different locations of the generator. To summarize, in this equation, the first term on the right represents the fluid inertia and the second term the total electromagnetic forces; the both terms have an influence on the pressure evolution.

5. The coupling

The coupling between the two thermo-acoustic elements and the MHD generator is not easy, because we must ensure the continuity of both pressure and velocity at the gas-liquid interface. Two possibilities can be envisaged to solve the problem, taking into account the fact that the two thermo-acoustic elements and the MHD generator are modeled separately.

The first method of coupling between the two models can be applied for standing-wave thermo-acoustic engines and is based on the characteristics obtained for the MHD generator, which give the pressure and velocity at the liquid-gas interface. From that, it is possible to deduce the input parameters for the heat source, including the introduced heat flux, and geometry parameters of the closed end. This is similar to an inverse problem in which the thermo-acoustic code is used by operating it from the cold source to the hot source. This method does not always give a physically acceptable result.

The second possibility is based on the concept of acoustic impedance. In this case, it is possible to define the correlation between pressure (p) and volume flow (U) by a relationship of the form: p = U Z, where the impedance Z is a complex quantity. This type of relationship can be defined for the thermo- acoustic part and the MHD part. Equaling the two impedances determines the working point.

6. The impedance method

The main program uses the thermo-acoustic and MHD calculation modules to calculate the impedances ZTA and ZMHD of the engines at their joint.

The thermo-acoustic engine impedance is calculated as: ZTA = pout/Uout. As pout and Uout, ZTA is a function of frequency ω, pressure amplitude at the stack entry pentry, total introduced energy Q, and cold temperature Tc. However, during the calculations, Tc and Q are fixed, so ZTA becomes a function of only two real parameters, ω and pentry.

The acoustic impedance of the MHD engine is calculated as ZMHD = pin/Uin. Due to the linearity of the used equations, pin is proportional to Uin. Thus ZMHD is only a function of the frequency, ZMHD =

ZMHD (ω). Therefore the difference between the thermo-acoustic and MHD engine impedances, ΔZ = ZTA – ZMHD, is also a function of ω and pentry.

A solution of the wave equations in the thermo-acoustic and MHD engines is obtained when the impedance difference ΔZ is zero. Therefore to find the solution, the roots of the equation ΔZ(ω, pentry) = 0 must be found. The program uses the Newton's method to solve this equation. An alternative root finding approach could be based on minimization of the impedance difference module.

7. An example of results

The following characteristics have been used to test the method:

Table 1. Some characteristics of the TA/MHD generator for the space application.

Heat source	~ 1000 K
Cold source	~ 600 K
Thermodynamic fluid	helium
Mean pressure	> 30 bars
Liquid metal	sodium or NaK
Electrical power	~ 500 Watts
Voltage	~50 to 100 Volts
Intensity	~5 to 10 Ampères
Total mass	~20 to 30 kg
Global efficiency	~50% of Carnot
Specific mass	~10 W per kg.

7.1. The main parameters used for the TA engine are:

Length of one of the two symmetrical loops: 1 m
Diameter of the tube of order of: 10 cm
Fluid: helium
Tube wall and stack plate material: stainless steel
Mean pressure: 5.1·106 Pa
Thermal energy introduced: 1600 W
Cold temperature: 324 K

7.2.The main parameters used for the MHD engine are:

Maximum diameter at the inlet: 15 cm
Length of the generator: 19 cm
Melt electric conductivity: 5.0·106 S/m
Melt density: 1000 kg/m3
Permanent magnetic field:
at the inlet: 0.35 T
at the outlet: 1.05 T
at the central core : 1.179 T

Number of the coil wires: 100
Gap thickness at the inlet: 6 mm
Capacitance C of the load: 3.9·10-5 F
Active resistance R of the load: 18.1 Ohm

7.3. The dependence of the impedance on the frequency is given below:

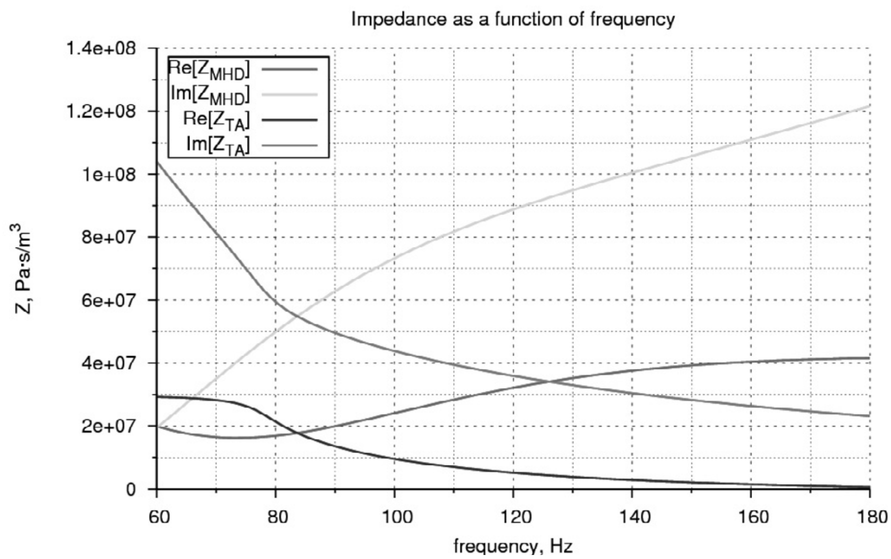

Fig. 4. TA and MHD impedances as functions of the frequency. Pentry=4.077·105 Pa.

And the corresponding frequency dependence of the temperature at the hot source is:

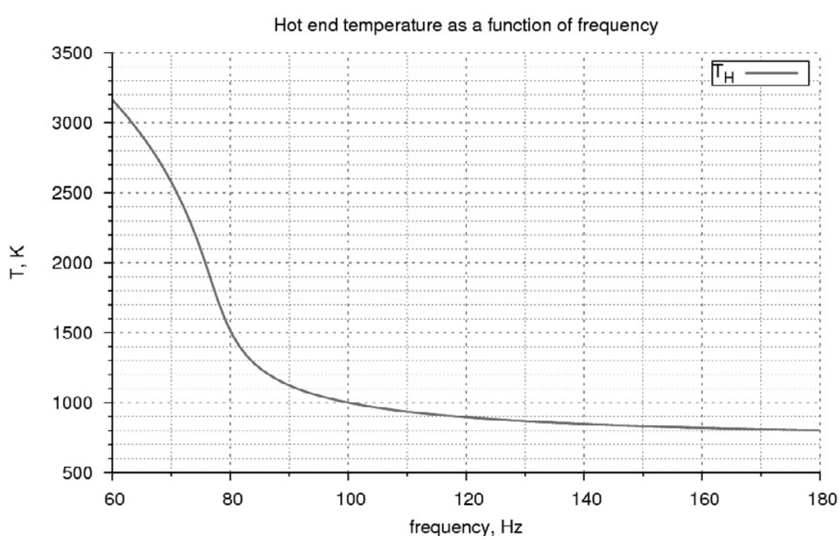

Fig. 5. Stack hot end temperature as a function of frequency. pentry=4.077·105 Pa.

It can be seen that there is a solution for coupling the thermo-acoustic and MHD engines at approximately 80 Hz frequency, corresponding to the temperature level of about 1300 K. This is too hot, but it is a first step of the coupling, and an optimization procedure has to be done.

7.4. The other results are the following:

Working frequency: 83.64 Hz
Hot end temperature: 1298 K
Pressure wave amplitude |pentry| at the stack entry: 4.077·105 Pa.
Pressure wave amplitude |pin| at the MHD entry: 3.794·105 Pa
Volume flow rate |Uin| in the MHD engine: 0.00658 m3/s
TA engine Carnot efficiency: 0.6407
TA engine efficiency: 0.4809
Induced magnetic field:
    at the cone inlet: (0.03945,-0.1613) T
    at the cone outlet: (-0.1765,-0.4330) T
    at the central core : (-0.016 -0.51) T
Melt velocity:
    at the gap inlet: 2.327 m/s
    at the gap outlet: 10.91 m/s
Load current |IR|: 7.442 A
MHD engine efficiency: 0. 6514
Total efficiency: 0.3132
Total power produced on the load: 501.2 W

8. Perspectives

Numerical models for thermo-acoustic and MHD generators are currently operational, the coupling is also operational. An optimization procedure has to be done in terms of efficiency and specific mass (the mass per unit of power), which is an important parameter for space application. Also the strength of the induced magnetic field must be reduced. Considering the thermo-acoustic element, existing models are still incomplete regarding the turbulence effects and scaling of heat exchangers subjected to a pulsating flow at zero mean velocity

The construction of an experiment to validate the performance of MHD generator is being defined. This experiment could be conducted in collaboration with the University of Latvia (Institute of Physics, University of Latvia, IPUL), an expert for conducting experiments with liquid sodium.

There are very important applications in electrical power generation by using the solar energy. In this case, the machine would be placed at the focus of a solar parabolic or cylindrically-parabolic collector.

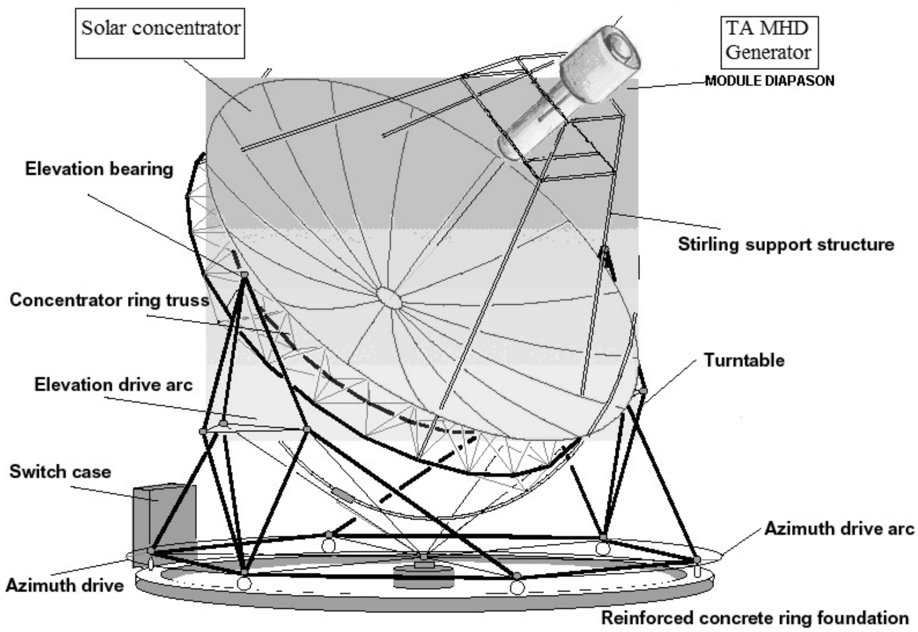

Fig. 6. An example of the TA-MHD generator using solar energy.

References

[1] Joussellin F. Alemany A. Werkoff F. and Marty Ph "MHD induction generators at weak magnetic Reynolds number - Part 1 Self-excitation criterion and efficiency" Europ. Journal of Méchanics, Vol.8B 1 (1989).

[2] Marty Ph.," Direct-current power generation in self-excited liquid metal magneto hydrodynamic generators" Magneto hydrodynamics, vol.27 no. 4, 455-60. USA. (1991).

[3] Ramee T., Roux JP., Alemany A: "TA MHD electrical generator study Engineering Baselins Deffinition" Rapport interne SA 5 11 2009.

[4] Swift G.W., A. Migliori, T. Hofler, and John Wheatly, "Theory and calculations for an intrinsically irreversible acoustic prime mover using liquid sodium as primary working fluid", J. Acoust. Soc. Am. 78 (2) August 1985.

[5] Swift G.W DeltaEC, Version 6.2, Users Guide, as of May, 2010

[6] Vogin C. "Etude d'un générateur thermo acoustique MHD pour une application spatiale " Thèse de l'Institut National Polytechnique de Grenoble, soutenue le 4 Janvier 2005.

[7] Vogin C., and Alemany A.,"Analysis of the flow in a thermo-acoustic MHD generator Journal of Mechanics / B Fluids, 26 (4), 479-493, (2007).